An Analysis of the most Frequent Operational Temperature of four District Heating Networks of Germany

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Abstract

Pre-insulated pipes according to EN 253:2019 that are used in District Heating (DH) networks comprise of minimum three layers. These layers are steel medium pipe, rigid polyurethane (PUR) foam as the insulation layer, and a polyethylene (PE) casing as the protection layer. Various studies show that the thermo-oxidation of the PUR foam is one of the most critical mechanism that determines the service-life of the pre-insulated bonded pipe systems. The deterministic approaches for service-life estimation considers the design temperature of the network e.g. 120°C, however the DH operational flow temperature is not constant. In recent decade, due to the decarbonisation trends and new artificial intelligent (AI) based techniques, the DH networks are optimized better than before and therefore, the DH operating flow temperature reduced to some extent. This temperature reduction affects the thermo-oxidation reaction speed, and the thermo-oxidation level of the PUR foam is very crucial to understand the adhesion of the PUR foam at the interface of the steel pipe and accordingly the service-life prediction of the pipe. Moreover, it affects the axial shear strength, which is necessary to impede the steel pipe movement that is caused by thermal expansion and to reduce the mechanical cyclic load. In this paper, the temperature changes of four different DH networks in Germany are analysed and the aim is to reveal the flow temperature of the in-operation DH pipes, Equivalent to Constant Continues Temperature (ECCT). The ECCT would be useful for different purposes such as thermo-oxidation analysis or to be utilize as a parameter in life-time prediction of the DH pipe.

Introduction

District Heating (DH) networks have evolved from their first appearance (Lund et al., 2014) until today, which according to (Buffa et al., 2019) they are in 5th generation now. In every generation, different changes can be identified in different parts of the system as well as in the production, distribution, and consumer sides. One major break-through in DH took place in gen 3 that pre-insulated bonded pipe systems have been introduced. This pipes according to (EN 253:2019) comprise of minimum three layers. These layers are steel medium pipe, rigid polyurethane (PUR) foam as the insulation layer, and a polyethylene (PE) casing as the protection layer. This technique has facilitated the implementation of the pipes in the ground faster than before. Because of the pre-insulation process in the factory, the quality of pipes were higher, plus no additional building for ducts out of concrete and no extra insulation layer such as mineral or glass wool was required. Additionally, it was more flexible in execution, less space needed in public area, cheaper and faster in execution. Therefore, it was possible to bury the pipes directly into the ground without any extra works such as sealing the hatches and ducts to inhibit additional heat-losses and controlling the thermal bridge at mount positions. However, the bounded pipes have a robust design; the utilities always try to run their system in an efficient way with integrating optimization techniques. A first step system optimization tries to adjust the flow temperature relative to the outdoor temperature. This means, for the mean daily ambient temperature below a certain degree Celsius there is a heating demand inside buildings, which is known as Heat Degree Days (HDD) and according to Germany Climate Resilience Policy Indicator (IEA, 2021) this temperature is 16°C. Therefore, the required energy to fulfil the demand needs to be regulated accordingly in the DH supply line. Thus, DH networks operate with a gliding system, in a way that the supply temperature could vary within a range that fits to its own network specifications, i.e. between 80°C to 130°C relative to outside temperature (Paar, 2013) (See Fig. 1).

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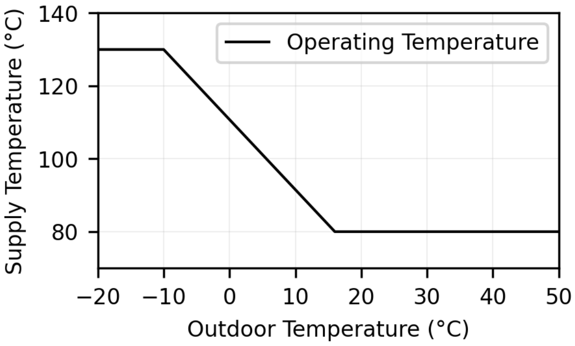

Fig. 1: Schematic operating temperature of a district heating designed for temperature range of 80°C to 130°C with gliding system.

Second step towards optimisation technique is heat demand profile prediction. The operational supply temperature is then modified not only based on outdoor temperature but also according to the probability of the heat demand inside buildings. As an example, at night the heat demand is low because the consumers turn their heating appliances off. Another example could be the working hours. Usually, the consumers are not at home during the working hours of the week and because of this, they consume less than during the hours that they are at home and therefore, the heat demand is influenced by the user behaviour. Alternatively, public and industrial buildings have small heat demand during weekends. However, the grid operators add hydraulic models to their system to supply the heat with minimum fluctuation in the carrier's temperature. Currently, DH systems are also under influence of Industry 4.0 (Lasi et al., 2014) with integrating assorted Artificial Intelligence (AI) techniques such as Machine Learning (ML) and Deep Learning (DL) for different purposes such as operation and maintenance (Langroudi & Weidlich, 2020; Mbiydzenyuy et al., 2021; Saloux & Candanedo, 2018).

All these complexities apply different loadings to the pipes. The one for temperature cycles is known as Thermal Fatigue. In DH systems, thermal fatigue dominantly controls the degradation of all three main components of the bonded pipe system due to cyclic fluctuations in temperature. Since the flow temperature in DH systems is not constant, it will be useful in different research area of DH systems to have an Equivalent Constant Continuous Temperature (ECCT). As an instance, it would be useful for researchers who are studying the rigid PUR foam degradation and the approximation of the annual thermo-oxidation. This value could also be utilize as a parameter in lifetime prediction of the DH pipes. Therefore, in this paper the operational temperature of four DH networks is analysed and discussed. This paper does not discuss the PUR ageing mechanism and the service-life of DH pipes itself, but about the ECCT of DH networks temperature that could be used in lifetime prediction of the pipes and foam thermo-oxidation process. Additionally, the temperature means and modes of the analysed networks are discussed.

Material and Methods

For this research, four sets of temperature data have been used. The collected data are in time-series format for two to three continuous years that are on hourly basis with two decimal places precision. The data period that is analysed for each network is summarised in Table 1. The measurement locations are at substation of each DH network according to description of each operator. These measurements have been conducted for both supply as well as return pipes.

Network	Data Period (Years)
A	2013-2015
B	2017-2019
C	2018-2019
D	2017-2020

Tab. 1: Period of analyzed substation temperature of each DH networks

Statistical analysis methods such as mean, mode, and normal distribution function have been employed for evaluating the time-series. To avoid biasing, a data-cleaning process have been applied for the data sets to remove the null and any unrealistic values.

Results

Before the analysis of the datasets, it is important to check the consistency of the data. If one wants to investigate the cyclic load based on the temperature alteration, the temperature difference (ΔT) at each oscillation is of importance. According to (EN 13941-1:2019) the number of equivalent full temperature cycles can be calculated from:

$$N_o = \frac{\sum n_i \bullet (\Delta T_i)^m}{(\Delta T_{ref})^m} \qquad \text{Equation 1}$$

Where

n_i	is the number of cycles with temperature range ΔT_i
ΔT_{ref}	is the reference temperature at which No is calculated
m	is the constant in the SN-curve

Since the aim of this paper is to shed light on the operational temperature values, any temperature drop below 65°C and 50°C respectively for supply and return pipes have been set as Limit Values (LV). The temperature below the LV have not been taken into consideration, although they have cyclic load effect on pipes because of the larger temperature difference according to equation 1. The LVs are not fixed and should be determined for each dataset. Hence, in the analysed dataset all the data points below the mentioned LVs including all the null points have been eliminated from the time series to avoid any adverse effect on the ECCT. The reason of the inconsistencies in data are not known but most probably, these could appear because of maintenance activities such as inspections and repairs. Other possibilities could be a failure in logging devices, place of logging, unexpected disturbance, revision of power plant, etc.

The statistical analysis has been accomplished on four datasets. As explained, DH systems run at higher temperature on colder weathers. Accordingly, in warm months, they supply around 65-70°C for domestic hot water, if no specific higher temperature is required. For instance, absorption chillers could utilize hot water energy instead of electricity for cooling but they need higher temperature as 70°C as an input, or in case of connection to industry, a minimum temperature might be required that needs to be satisfied even in warm seasons. In cold months, DH systems supply above 100°C for both domestic hot water and heating. To understand the mean temperature influence of warm and cold weather, three separate analysis are performed for warm, cold and annual season. To be able to compare the networks, in this work April is set as starting month, which is the commencement of the warm season. The warm season lasts till the end of September and the cold season begins in October. The reasoning of this arrangement is to have a full cold season in the annual analysis.

Fig. 2 represents a full year of the operating temperature of four DH networks. Network A has an almost constant run in warm season slightly above 90°C and surprisingly it keeps the same flow with light increase in winter season. No significant change of mean temperature in network A between warm and cold season has been detected. In network B some minor peaks are detectable in April-May and then it plateaus around 80°C. The cold season in network B shows the expected temperature fluctuations and the highest peaks from February to April. The annual mean temperature in network B is roughly the mean of cold and warm season means. Comparing the operational temperature patterns, the network C is exceptionally different from the other networks. Although the fluctuation in network C is high, no extreme peak detected in the cold season. The mean value in the network C is the highest in all networks around 95°C. Network D is very similar to network B with an annual mean around 80°C. In all networks the mean temperature of the return pipes are higher in warm season and lower in cold season.

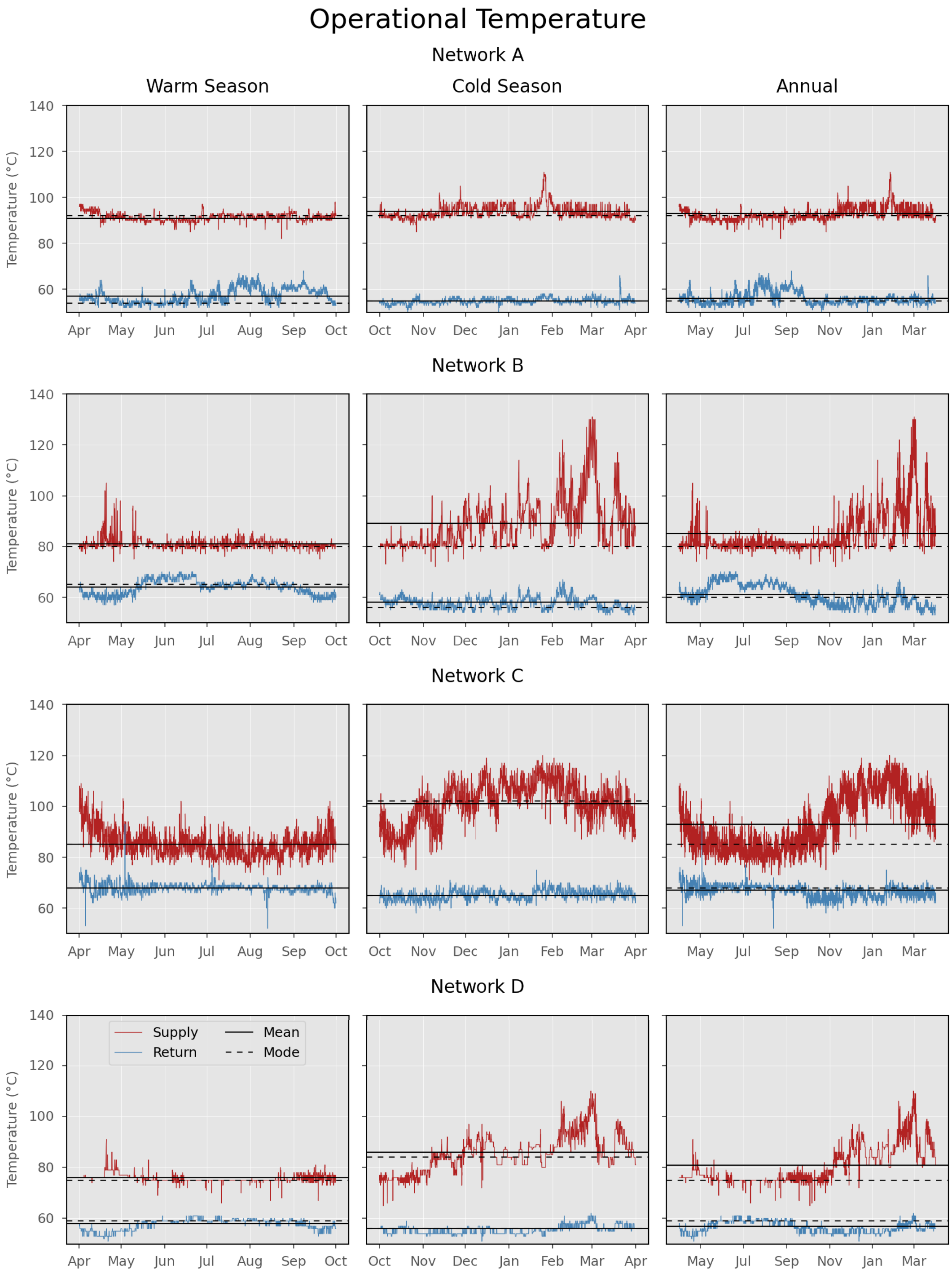

Fig. 2: An annual and seasonal operational temperature pattern of four district heating networks in Germany

Discussion

A statistical analysis of three years for network A, B, and D and two years for network C is summarized in Table 2. The maximum and minimum supply temperature values are found in network B with 131°C and 63°C. The temperature at 150°C and above triggers other form of ageing mechanisms that do not appear in DH systems (Vega et al., 2018), however no such high temperature has been observed in data sets. The minimum return temperature could not be discussed completely, since different continuous temperature drop to 0°C have been detected in datasets and it was set to LVs. However, the maximum return value has found in network C with 99°C.

Since the dataset is hourly basis, no conversion or further calculation is required to find the equivalent continuous temperature and the mean value could be directly counted as ECCT. Interestingly, the supply ECCT value of the networks are in range of 80°C to 95°C.

	Supply (°C)				Return (°C)			
Network	A	B	C	D	A	B	C	D
Min	82	63	64	65	50	51	50	51
Max	120	131	124	110	71	70	99	68
Mean	93	85	94	81	57	59	67	58
Median	92	81	94	77	56	59	67	58
Mode	92	80	85	75	55	55	68	59
Percentile 25	91	80	85	75	55	56	65	56
Percentile 75	93	86	103	85	58	62	69	59

Tab. 2: Statistical analysis of continuous two-three years of operational temperature for supply and return pipes of four district heating networks in Germany

The box-plot of the supply temperatures in Fig. 3 is explaining the distribution of the temperature data of Fig. 2. The box-plot is giving a clear picture of the temperature ranges in terms of occurrence. The temperature 5°C dispersion of each network varies. This could be because of geographical location and/or the applied optimisation technique. In the annual analysis of the network A, B, and D, the first quartiles (Q1) are close to second quartiles (Q2) with a maximum difference of 2°C. Except network C, the third quartiles (Q3) in both warm and cold seasons are below 100°C and considering the annual distribution it drops to below 95°C. Additionally, the annual maximum value of these networks are below 95°C as well. Network C as discussed before, is the only network in which higher temperatures in the system could be count in the distribution function and not as outlier. However, the form of operation of Network C might not be very common in DH systems, but for a broader conclusion, it will be included in our further considerations.

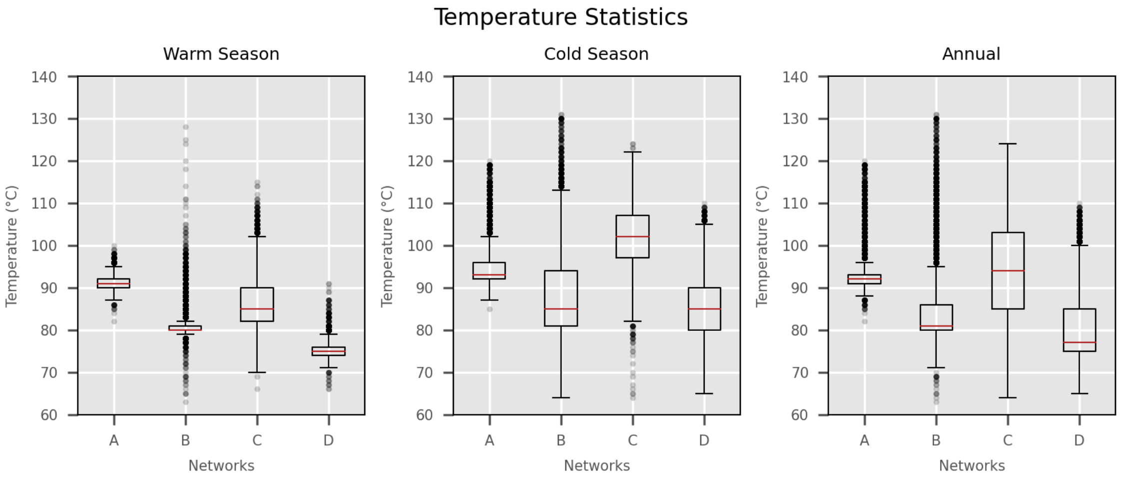

Fig. 3: Box plot of the supply operational temperature of four district heatings in Germany

A mean of ECCTs of available years could be determined as a holistic value of the operational temperature of DH systems. Here, the mean ECCT could be calculated as 88°C for supply and 60°C for return pipes.

The ECCT could be very helpful to understand the ongoing ageing of the in operation pipes. This could be possible with collecting the damage statistics and correlate the mean decommission age with ECCT of the DH network. The ECCT of 88°C is of importance in two aspects. First, the annual average of the thermo-oxidation pipe could be approximated. Second, the yearly monitoring of this value could help to understand the rate of thermo-oxidation of PUR, whether it is negative, positive, or relatively constant and provide practical information of DH pipes that are in operation.

Conclusion

Based on the optimized operation modes of the DH networks in Germany, the operational temperature is relative to outdoor temperature, heat demand profile and the largeness of the network. The statistical analysis of operational temperature changes at substations of four DH networks for two to three continuous years revealed that the current ECCT is about 88°C. This rate may also sink in the following years to a lower value because of decarbonisation trends such as advanced optimisation techniques, digitalization of the DH systems, and construction of the energy efficient buildings. Although, some high peaks up to 131°C have been detected, the frequency that pipes are subjected to such high peaks are low and they are counted as outliers in the annual temperature distribution analysis. The ECCT could be monitored yearly/seasonally for understanding the rate of thermo-oxidation of the PUR. Also, it could be used as a parameter for lifetime estimation of DH pipes in combination of damage statistics and thermal fatigue analysis. This could help to determine the service-life of the pipe and consequently calculating of the Remaining Useful Life (RUL).

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